THE EFFECT OF MATERIAL DISCONTINUITY ON THE FLANGES OF AXIALLY COMPRESSED STEEL CONES

O. Ifayefunmi
Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia
Centre for Advanced Research on Energy (CARe), Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia

Dhiya Danial Ibrahim
Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia

ABSTRACT

This paper aims to present experimental data on the buckling behavior of mild steel truncated cones with local material discontinuity on the flange of a percentage of the hoop length of the small ends of the cone subjected to axial compression. Six truncated cones were manufactured with nominal geometry given by \( r_2/t = 50.0 \), \( r_2/r_1 = 2.0 \), \( h/r_2 = 2.24 \), \( \beta =12.58^\circ \) and wall thickness, \( t = 1.0 \text{ mm} \). Cones were manufactured from welded mild steel plate with 6 mm thick integral top and bottom flanges. The flange is fully welded to the big end of the cone. While at the small end of the cone, material discontinuity is introduced. Results of experimental tests reveal that two nominally identical cones failed at almost the same magnitude of collapse load (49.35 kN and 50.39 kN). For axially compressed cones with material discontinuity at the top flange applied to a fraction of the circumference, experimental results also show that as the material discontinuity increases, the collapse load decreases. In conclusion, for axially compressed cones, material discontinuity on the flange of the fraction of the circumference leads to a reduction in the buckling load of the cone.

Key words: Buckling, material discontinuity/crack, axial compression, mild steel, cones

http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=6
1. INTRODUCTION

Thick cones have been a subject of interest in the offshore industry especially for applications such as piles for holding jackets when driven into the sea bed and as transition elements between two cylindrical shells of different diameter. When in use for such application, the cones must be manufactured with integral flanges at both ends. Flanges on cone ends can be manufactured via several approaches. Some of the common methods employed in fabricating the cone and its flanges are: (i) machining both the cone and the flanges as an integral unit using Computer Numerically Controlled (CNC) machining, and (ii) manufacturing the cone and the flanges as separate entities and later joined them together to form one piece using welding or other joining techniques. The latter approach has received much interest because of the ease of manufacturing and low cost involved. In addition, for the joining process, the use of welding techniques is most preferable because it is a reliable and efficient metal joining process. Although, it is evident that during the welding process of the cone and the flanges, there is a tendency of having some portion of the circumference of the cones with material discontinuity/crack. This has been attributed to the effect of different quantities of heat flux and the quality of weldments thereby resulting in heterogeneity in the heat affected zone induced by the welding process, [1].

The presence of such material discontinuity/crack impose imperfection on the conical shell thereby resulting in a considerable loss of load carrying capacity of the structures. However, the design of such structures is aimed at its safe performances during routine operation. Imperfection sensitivity of conical shell is not a new topic. Previous researches reveal that the extent of sensitivity of conical shells to imperfection greatly depends on the cone geometric parameter and boundary conditions, [2]. Research into the influence of initial geometric imperfection can be found in [2 – 13]. Whilst, research on the influence of imperfect boundary conditions are reported in [14 – 19].

It is surprising to see that despite the large amount of work that has been done on the imperfection sensitivity of conical shells, there is lack of experimental data on the influence of material discontinuity/crack on the buckling load of conical shells. Recent numerical investigation into the buckling behavior of cones with crack subjected to axial compression can be found in [20 – 21]. In [20], the crack was located in the middle of the cone and the effect of material discontinuity/crack length and crack orientation were studied. While, in [21], the material discontinuity/crack was assumed to be introduced in the edge support at the top of the cone. The choice of the top end of the cone is borne to the fact that collapse and spread of plastic strain of relatively thick cones is mainly localized within the small radius ends of the cones, [22 – 26].

Motivation for the current work originates from the conclusion of a recent research on the ‘effect of material discontinuity on the flanges of axially compressed cylinder’ where it was concluded based on experimental results that there is no significant influence of material discontinuity as a fraction of the cylinder circumference on the load carrying capacity of the cylinder, [27]. Meanwhile, this conclusion is contrary to the results obtained for conical shells using ABAQUS finite element analysis, where the buckling load of the cone is seen to be significantly influenced by the presence of material discontinuity on the flanges of the small end of the cone, [21]. Hence, the need to provide experimental data in this area of study become increasingly important.

The present work concentrates on the effect of material discontinuity/crack along the flange of welded mild steel cones on the buckling behavior of cones subjected to axial
In the present study, six laboratory scaled mild steel cones were manufactured and all the cones were subjected to axial compression.

2. METHODOLOGY

The section provides the detail method employed in this paper, starting from conical specimen geometry and material data extraction, conical specimen manufacturing and conical specimens testing (i.e., axial collapse test).

2.1. Geometry of Conical Specimens

Consider a truncated cone with small radius, \( r_1 \) and big radius, \( r_2 \), and uniform thickness, \( t \) as sketched in Figure 1a. Assume that the height of the cone is given by \( h \), and the cone angle is \( \beta \). Six truncated cones were manufactured from flat mild steel plate with nominal geometry given by: \( r_2/t = 50.0 \), \( r_2/r_1 = 2.0 \), \( h/r_2 = 2.24 \), \( \beta = 12.58^\circ \) and wall thickness, \( t = 1.0 \) mm. These specimens were manufactured with welded top and bottom flanges. Section through the cone and the flanges with the nominal dimensions (in millimeter) is presented in Figure 1b.

![Figure 1](image1.png)

**Figure 1** Geometry of (a) truncated cone, and (b) section through the cone with nominal dimensions in mm

Circumferential crack of different lengths, \( s_i \), as a fraction of cone hoop length, were introduced on the flanges of the specimens during the manufacturing process as sketched in Figure 2a. All the specimens are assumed to be subjected to axial compression. Both the material discontinuity and the axial load were applied at the small radius end of the cone (see Figure 2a).

![Figure 2](image2.png)

**Figure 2** Sketch of the cone with material discontinuity on the flanges at the top end of the cone (a), and photograph of manufactured cone with material discontinuity at the top end of the cone
The choice of the top end of the cone is borne to the fact that collapse and spread of plastic strain of thick cones is mainly localized within the small radius ends of the cones. Figure 3 depicts the plot of typical load versus compression extension curve for plastic buckling behavior of cones subjected to axial compression and the corresponding spread of plastic strain distribution through the shell wall thickness at collapse.

![Figure 3](image)

**Figure 3** Typical plot of axial load versus compression extension for plastic buckling of cone, with the corresponding collapse mode and the spread of plastic strain at collapse through the shell wall thickness

It is evident from Figure 3 that for axially compressed thick cones, there is bulging out in the neighborhood of the small radius end of the cone. Similarly, the spread of the plastic strain always appears at the small radius end of the cone. Further details can be found in [22 – 26].

The material properties of the mild steel plate were obtained through standard tensile test using INSTRON testing machine. Four flat tensile samples were cut-out from the 1 mm flat mild steel plate and machined according to British Standard BS EN 10002-1 2001, [28]. All tensile samples were subjected to uni-axial tensile test at the rate of 1.0 mm/min. The shells and tensile specimens were not stress relieved at any stage of their manufacturing.

### 2.2. Manufacturing of Conical Specimens

To manufacture the conical shell, several processes were carried out. First, the flat 1 mm mild steel plate is cut into the desired specimen dimension using abrasive waterjet machine. Again, the 6 mm mild steel plate is cut into the desired flange dimension, i.e., outer diameter of 140 mm for both top and bottom ends, inner diameter of 50 mm at the top end and inner diameter of 100 mm at the bottom. The inner diameter of the flange at the top and bottom correspond to the top and bottom diameter of the conical specimen. Because the cut-out specimens and the flanges were exposed to water and abrasive during the cutting process, immediately after the cutting process, they were removed, thoroughly cleaned and spray with lubricating oil to prevent them from rust. Then, the cut-out specimens were rolled into the desired conical shape using the conventional rolling machine. During the rolling process, there are two controlling knobs to be adjusted until the desired shape is achieved. For conical model, because of the difference in diameter at the top and bottom ends, the number of turn on one side must be less than that of the other side. Next, the ends of the rolled models were joined together using the Metal Inert Gas (MIG) welding process. After welding the specimen, then the flanges were welded to the conical specimens as exemplified in Figure 4. During the welding process of the flanges to the conical shells, the flanges were fully welded to the big radius end of the cone. Whereas, on the small radius end of the cone, material discontinuity/circumferential crack of varying lengths, $s_i$, which is a fraction of the cone small
ends circumference were introduced on the specimen. Figure 5 depicts a photograph of closer look of conical model with material discontinuity on the small end of the cone.

A total of six conical models designated by [1, 2, 3, 4, 5 and 6] were manufactured. The ratio of circumferential crack length, $s_i$, to the cone small end circumference, $2\pi r_1$, was varied from 0.0 to 0.5. Model 1 is assumed to be perfect with no material discontinuity, i.e., $s_i/2\pi r_1 = 0.0$). While models 2, 3, 4, 5 and 6 has material discontinuity introduced into them with a magnitude, $s_i/2\pi r_1$ of 0.1, 0.1, 0.15, 0.2 and 0.5, respectively. To ensure repeatability of experimental data, two conical models with the same magnitude of material discontinuity were considered for $s_i/2\pi r_1 = 0.1$.

![Figure 4](image_url)

**Figure 4** View of MIG welded cone (model 1) with top and bottom flanges.

![Figure 5](image_url)

**Figure 5** A close look of cone (model 5) with introduced circumferential material discontinuity on the flanges of the small end of the cone.

### 2.3. Axial Collapse Test

Six conical models 1, 2, 3, 4, 5 and 6 were subjected to axial compression using Universal Instron 8802 Machine. During the experiments, the specimen was placed between the 150 kN INSTRON machine. It was assumed that the platen of the INSTRON machine in addition to the flanges on the cone will help to provide the desired boundary conditions at both ends of the cone as shown in Figure 6. Incremental axial load was applied at the rate of 1.0 mm/min from the top of base plate to the small radius end of the cone. During the experiment, the axial shortening of the specimen were recorded using the machine controller.
3. RESULTS AND DISCUSSIONS

First, the material properties of the material used in fabricating the conical specimen were obtained from uni-axial tensile test. Four differently oriented flat tensile samples, S1, S2, S3 and S4 were cut out from the 1 mm flat mild steel plate. Samples S1 and S2 were cut in the lateral direction, while samples S3 and S4 were cut in the axial direction. Table 1 gives the summary of the material data which were obtained in the tests. In order to obtain the yield stress of the material, the upper yield was determined using 0.2% proof stress.

Table 1 Material data obtained from uni-axial tensile tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>E (GPa)</th>
<th>Upper yield (MPa)</th>
<th>UTS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>200.5</td>
<td>225.4</td>
<td>316.2</td>
</tr>
<tr>
<td>S2</td>
<td>218.8</td>
<td>229.9</td>
<td>320.6</td>
</tr>
<tr>
<td>S3</td>
<td>228.2</td>
<td>206.3</td>
<td>311.1</td>
</tr>
<tr>
<td>S4</td>
<td>212.4</td>
<td>212.4</td>
<td>315.6</td>
</tr>
</tbody>
</table>

From Table 1, it can be seen that the material properties are anisotropic, i.e., there is a difference in the material data for different orientation. For example, the tensile samples in the lateral direction (S1 and S2) exhibit higher yield stress and ultimate tensile stress (UTS) as compared to samples in the axial direction (S3 and S4). Poisson ratio, \( \nu \), of the mild steel plate was assumed to be 0.3 (taken from material data sheet).

Prior to testing, series of measurements were taken on all the conical models. First, the wall thickness was measured using micrometer screw gauge at ten different equidistant point along the length and ten points across the circumference (36 deg.), leading to 10 x 10 = 100 measuring points. The average \( t_{ave} \), minimum \( t_{min} \) and maximum \( t_{max} \) and standard deviation \( t_{std} \) wall thickness are provided in Table 2. Next, the inner and outer diameters of the cones were measured using digital Vernier caliper at five equally spaced diameters. The average mid-surface diameter is presented in Table 3. Finally, the cone height, cone slant length and/or cylinder axial length were measured using digital Vernier caliper. The corresponding results are given in column 4 and 5 of Table 3, respectively.
Table 2 Measured values of the wall thickness

<table>
<thead>
<tr>
<th>Model</th>
<th>( t_{\text{min}} ) (mm)</th>
<th>( t_{\text{max}} ) (mm)</th>
<th>( t_{\text{ave}} ) (mm)</th>
<th>( t_{\text{std}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.966</td>
<td>0.971</td>
<td>0.969</td>
<td>0.00109</td>
</tr>
<tr>
<td>2</td>
<td>0.959</td>
<td>0.972</td>
<td>0.966</td>
<td>0.00366</td>
</tr>
<tr>
<td>3</td>
<td>0.959</td>
<td>0.969</td>
<td>0.964</td>
<td>0.00264</td>
</tr>
<tr>
<td>4</td>
<td>0.959</td>
<td>0.968</td>
<td>0.963</td>
<td>0.00235</td>
</tr>
<tr>
<td>5</td>
<td>0.965</td>
<td>0.979</td>
<td>0.969</td>
<td>0.00166</td>
</tr>
<tr>
<td>6</td>
<td>0.964</td>
<td>0.972</td>
<td>0.969</td>
<td>0.00136</td>
</tr>
</tbody>
</table>

Table 3 Measured values average mid-surface diameter, average cone height and average cone slant length for all models

<table>
<thead>
<tr>
<th>Model</th>
<th>( D_{\text{top}} ) (mm)</th>
<th>( D_{\text{bottom}} ) (mm)</th>
<th>( h_{\text{avg}} ) (mm)</th>
<th>( L_{\text{avg}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.22</td>
<td>98.72</td>
<td>109.82</td>
<td>114.72</td>
</tr>
<tr>
<td>2</td>
<td>50.23</td>
<td>98.714</td>
<td>110.09</td>
<td>114.23</td>
</tr>
<tr>
<td>3</td>
<td>50.174</td>
<td>98.314</td>
<td>109.70</td>
<td>114.08</td>
</tr>
<tr>
<td>4</td>
<td>49.825</td>
<td>98.603</td>
<td>110.30</td>
<td>114.11</td>
</tr>
<tr>
<td>5</td>
<td>50.059</td>
<td>98.9</td>
<td>109.94</td>
<td>113.79</td>
</tr>
<tr>
<td>6</td>
<td>50.139</td>
<td>98.7</td>
<td>110.02</td>
<td>114.14</td>
</tr>
</tbody>
</table>

During the experiments, the compression extension and the corresponding load at each increment were measured by the machine. Figure 7 depicts the plot of collapse load corresponding to different conical model, i.e., perfect model (model 1) and imperfect models (i.e., model 3 and model 4 with material discontinuity, \( s_i/2\pi r_1 \) of 0.1 and 0.15, respectively). The curves were nearly linear up to the collapse load except for the settling down stage at the beginning of the experiments. From Figure 7, it can be seen that increasing the material discontinuity leads to a reduction in the collapse load maximum extension at collapse of the conical specimen. Hence, it is apparent that the presence of circumferential crack on the flanges of the cone has considerable effect on the reduction of the load carrying capacity of the cone for all the radius-to-thickness ratio considered. This is contrary to the case of cylindrical shell presented in [10]. The collapse load for all conical model subjected to axial compression test are given in Table 4. From Table 4, it can be observed that the repeatability of experimental data for two nominally identical conical specimen with material discontinuity, \( s_i/2\pi r_1 \) of 0.1 was good (49.35 kN versus 50.39 kN). The error within the pair was 2%.

Figure 7 Plot of axial load versus compression extension for conical specimen with different magnitude of material discontinuity.
Table 4 Experimental collapse load for conical specimen with different magnitude of material discontinuity.
Note: $s_i/2\pi r_1$ = magnitude of circumferential crack to the cone small end circumference thickness

<table>
<thead>
<tr>
<th>Models</th>
<th>$s_i/2\pi r_1$</th>
<th>Collapse load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>50.90</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>50.39</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>49.35</td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
<td>45.92</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>39.06</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>40.08</td>
</tr>
</tbody>
</table>

Figure 8 presents the plot of collapse load corresponding to different imperfect conical models having local material discontinuities of a percentage of the hoop length against increasing length of material discontinuity. The vertical axis is normalized by the collapse load for the perfect cone (model 1). This will provide a common scale for both the collapse load for the perfect and imperfect cones. In addition, it will ensure comparison of corresponding normalized values (collapse load for imperfect cones) for different datasets with the original values (for perfect cone).

It can be seen from Figure 8 that material discontinuity extending by 20% of the circumference of the cones will cause a drastic reduction in its buckling strength, about 24% reduction in the load carrying capacity. Also, it appears from Figure 8 for $s_i/2\pi r_1 \geq 0.2$, the line remains linear i.e., a fraction of 0.2 material discontinuity on the circumference of the cones is enough to cause maximum reduction in its buckling strength. This result appears to be in agreement with published work in open literature, i.e., load carrying capacity of the conical shell structure reduces as the local material discontinuity at the flange increases [3, 4].

4. CONCLUSIONS
Repeatability of experimental data for two nominally identical conical shells with material discontinuity/circumferential crack along the welded flange subjected to axial load was good. Based on the experimental results, it can be inferred, that the magnitude of circumferential crack length along the flange of the truncated steel cone subjected to axial compression will lead to a considerable reduction in the load carrying capacity of the cones. Again, it can be said that material discontinuity extending by 20% of the circumference of the cones is enough
to cause maximum reduction in its buckling strength. However, this might be different for other geometry as reported for circular cylinder in [10].

ACKNOWLEDGEMENTS
The authors will like to acknowledge the financial support received from Centre for Research Innovation Management, Universiti Teknikal Malaysia Melaka under the auspices of MyRA 2015 (K11004).

REFERENCES


The Effect of Material Discontinuity on the Flanges of Axially Compressed Steel Cones


